1.0 Introduction

1.1 Vision

The Space Technology Panel's recommendations for technology investments derive from a vision of the Air Force in space in the 21st century, in which the Air Force has achieved *survivable, on demand, real time, global presence that is affordable.* This vision represents a *revolutionary* increase in capabilities for the Air Force and is achievable with targeted Air Force technology investments and adaptation of commercial developments. These technology investments will enable the US to maintain military superiority by the exploitation of space through four themes:

- Global Awareness
- Knowledge on Demand
- Space Control
- Force Application

1.2 Background

This report is a part of the Scientific Advisory Board's (SAB's) response to the challenge by Secretary of the Air Force Sheila Widnall and the Air Force Chief of Staff General Ronald Fogleman to "search for the most advanced air and space ideas and project them into the future."[2]

This report identifies the space technology investment areas for the Air Force that will provide substantial and affordable improvements to USAF space capabilities over the next 10-30 years. The Secretary and the Chief of Staff levied this challenge because of the "blistering" pace of technological change and the need to adapt swiftly to new developments. Specifically, the New World Vistas participants were challenged to:

- Provide a ten year technological forecast
- Predict how the explosive rate of technological change will impact the Air Force over the next ten years
- Identify fields of rapidly changing technology and assess their impact on the modern Air Force
- Identify those areas which will most likely revolutionize the 21st century Air Force
- Predict the impact of these technological changes on affordability of Air Force weapons systems and operations
- Predict Science and Technology (S&T) areas where the Air Force can minimize its investment and turn to the commercial world for technology development

2. Letter from SECAF Widnall and CSAF Fogleman to Dr. Gene McCall, New World Vistas Challenge for Scientific Board (SAB), 29 November 1994

- Highlight opportunities for dual use, possibilities for defense conversion, and mechanisms for capitalizing on technology advancement in the commercial sector
- Identify areas where the Air Force can rely on, or partner with, commercial industry for technology development
- Identify the areas where the Air Force is not the innovator, but a large high tech customer—offer advice on how the Air Force can be a better customer
- Predict S&T areas that the Air Force will have to develop, where no commercial market exists or will likely develop—highlight related industrial base issues
- Offer advice as to whether the Air Force lab structure is consistent with these new vistas and what changes, if any should be made
- Offer advice as to whether the current SAB charter is consistent with those new vistas, and what changes if any, should be made
- Evaluate proposals in light of how the Air Force contributes to the joint team[3]

Twelve panels were formed to respond to Air Force leadership's tasking. These panels were: Aircraft and Propulsion, Attack, Directed Energy, Human Systems/Biotechnology, Information Applications, Information Technology, Materials, Mobility, Munitions, Sensors, Space Applications, and Space Technology.

In light of the Secretary's and Chief of Staff's challenge, the Space Technology Panel developed a specific charter to guide and focus its efforts, and determined to:

- Identify new technologies for space applications in a 10-30 year timeframe that will offer
  - Fundamental improvements in Air Force capabilities
  - Significantly lower life cycle costs for future capabilities
- Consider the impact of commercial or dual-use technologies for space for the future and identify the technology path for incorporation into Air Force systems
- Seek out technologies that may lead to new paradigms in space applications

1.3 Assumptions

The recommendations contained in this report rest on the following key assumptions:

- Many nations and industries will be active and competitive in space
- Increasing reliance on space systems for military functions will add a new dimension to the vulnerability of US space systems and operations
- Although the commercial sector will lead in certain areas of technology driven by consumer demand, it will not lead in other sectors of military technology

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3. Letter from SECAF Widnall and CSAF Fogleman to Dr Gene McCall, New World Vistas Challenge for Scientific Advisory Board (SAB), 29 November 1994

- Current understanding of the laws of physics must bound any recommendations for technology investment

1.4 The Current Situation in Space

Space will continue to be the proverbial high ground for the foreseeable future. Operation Desert Storm showed that space assets integrated with air, ground, and sea assets can play a critical role as force enhancers in fighting and winning conflict. Senior Air Force leadership[4] asserts that "space systems signal America's stature as a world power and aerospace nation. Control of space and access to it are fundamental to economic and military security. Ask the 20 foreign countries who will have space capabilities by the year 2000: a presence in space implies influence, power and security."

The space enterprise can be divided roughly into four areas:

- Launch systems
- Spacecraft bus systems
- Spacecraft payload systems
- Spacecraft operations

In the area of launch systems, despite the recent development of small launch vehicles, US launch capability is dominated by an old, unresponsive, and relatively expensive set of launchers. Foreign launch systems have taken a substantial fraction of the world market, and the number of countries able and willing to launch payloads is continuing to increase. In the area of spacecraft bus technology, the US is in a leading position; the one major area where other countries have taken the lead is in spacecraft propulsion, where US technology is behind what has been accomplished in the former Soviet Union. The US is still leading in the integration and operation of spacecraft payload systems both from the component level into spacecraft and in the development of constellations of spacecraft. *This leading position is due to previous government investments in research and development in space technology*; maintaining this lead in the future will depend on the technology investments that the US government *and* private sector make today.

The reduction of resources available to the DoD in the post-Cold War era means that DoD investment in space technologies and space systems must be firmly rooted in the goal of affordable systems. To this end, the DoD must plan its technology investment with a clear view of technological advances in the commercial world. It is undesirable and unnecessary for the DoD to develop every technology for its space systems on its own. There are many technologies that the commercial sector will develop that the military can adapt for its use with minimal investment. On the other hand, there will always be unique requirements for military systems that necessitate the use of technologies that have no commercial application, that push the performance limits of dual-use technologies, or whose timescale and risk are not attractive to thecommercial sector. The DoD should carefully target its investments in technology to achieve the highest possible return. Technologies that are candidates for DoD investments fall into one of three possible categories:

4. Hon. Sheila E. Widnall, Secretary of the Air Force, September 1993

- Revolutionary technologies in which the DoD must invest vigorously, because they are critical to the military mission and have little or no application in the commercial sector; without DoD investment, these technologies will not advance. These technologies will enable a *substantial increase in the exploitation of space* by the DoD. They will enable functions that are currently unaffordable or technically impossible.
- Evolutionary technologies in which the DoD should invest, because they are similarly critical to the military mission and have little or no commercial application. These technologies will enable gradual advances that over time can significantly improve the performance or reduce the life-cycle costs of military systems.
- Technologies in which little DoD investment is required, because they will be led by the commercial sector. In these areas, the DoD should carefully monitor the progress that industry is making and invest only to the level necessary to adapt commercial technologies to the military mission.

The DoD should not underestimate the benefits of a healthy synergism between military and commercial research and development.

The Air Force's investment in space technology has fallen in recent years both as a fraction of Total Obligation Authority (TOA) and as a fraction of spending on research and development. The inception of the Strategic Defense Initiative Office (SDIO) in 1983 brought the primary Air Force space technology programs under the SDIO umbrella. During the heyday of SDIO, total DoD investment in space technology programs was more than $500M/year. The primary emphasis during this time was highly survivable space technology development and demonstration. In addition, major programs were initiated under the SDIO umbrella in active and passive space sensors, radiation-hardened electronics, advanced high-data-rate communications, high-efficiency and high-power solar arrays, and high-density power storage technologies along with cryocoolers and other related structural technologies. Great emphasis was placed on technologies and systems that were highly survivable against a variety of threats including laser, nuclear, and microwave effects. The evolution of SDIO into the Ballistic Missile Defense Office (BMDO) and the subsequent program direction to address theater missile defense had a negative impact on the space technology development budget and, as a result, space technology investment has decreased from $500 M/year to $200M/year. This dramatic decrease in space technology development investments will have a serious impact on the dominant position of the US in space systems development, both commercial and military, for years to come.

Air Force investment in space technology is grossly inadequate. The current situation is similar to the state of affairs earlier in this century when the US lead in aircraft technology faltered and a sustained effort was required to recapture that lead. The exploitation of space for military advantage requires aggressive and continuous investment.

1.5 Space Technology and Space Systems in the Future

In the next ten to twenty years, the commercial world will see the development of four types of space-based systems that will be available to both friendly and unfriendly nations, corporations, and individuals on a worldwide basis. These systems will provide commercial services but will also be militarily useful. In addition, these systems will either involve other countries that build or purchase them or will involve international consortia of investors. These systems will lead to the growth of new service industries based around their use that will be economically powerful. (A current example is the Global Positioning System (GPS); the growth of civilian users, including the FAA, is now creating a dilemma about the compatibility of easy access to precision GPS with the DoD's need to maintain a competitive military advantage.)

Four types of commercial services that will be available are:

- Global positioning and navigation services. While the DoD already has GPS, other countries are developing equivalent systems or augmenting the existing one; similar capabilities will be available through the development of personal communication systems. They will enable navigation with an accuracy at least several tens of meters.
- Global communication services. Several systems have already been proposed, such as Iridium, Globalstar, and Inmarsat-P. These systems will provide universal communications services between mobile individuals to almost any location on the surface of the Earth. These systems will work transparently with local cellular systems and will enable rapid telecommunications development in underdeveloped parts of the world.
- Information transfer services. These services will enable data transfer between any two points on the surface of the Earth at rates ranging from a few kilobits per second to gigabits per second. Proposed systems include Orbcomm, Spaceway, Cyberstar, and Teledesic. Individual users will be able to access large amounts of data on demand. Direct TV from direct broadcast satellites is a harbinger of what will be possible.
- Global reconnaissance services. These services will provide commercial users multispectral data on almost any point on the surface of the Earth with meter-scale resolution. This data will span the range from the radio frequencies (RF) to the infrared (IR) through the visible into the ultraviolet (UV). This information will be available within hours of a viewing opportunity and on the order of a day from the time of a request. Proposed systems include improvements to the French SPOT as well as Orbimage, World View, and various types of radar satellites.

Each of these services will be part of the global infosphere. It will be possible for persons of means to locate themselves on any point on the Earth, communicate both by voice and computer to other points on the Earth, and have a good picture of the local environment. Both the services and the technologies that enable them will be commercially available all over the world. Given the enormous magnitude of the commercial market, military and NASA communications will have to be fully integrated with and technologically dependent on the exploding market-driven communications technologies.

Nevertheless, there will be military-specific needs that are not encompassed by these four types of commercial services:

- Geographically selected denial of high-precision global positioning information (sufficient for weapons delivery) to an opponent, and assured friendly access to those same services;
- Assured access to communications that are robust against jamming and tampering and/or covert, including local surge capacity to deployed forces;
- Assured relay of very-high-data-rate intelligence information from geosynchronous distances;
- Day/night all-weather reconnaissance of low-contrast stationary and moving targets with hyperspectral imaging and in the shortest possible time;

The proliferation of space applications at affordable prices will tend to offset the current US military edge. Capabilities in these military-specific areas will enable the US military to have the advantage over an opponent who is also exploiting the infosphere.

1.6 Space Technology Developments in the Commercial World in the Next Twenty Years

To deliver the services described above in a competitive environment, the commercial world will invest in bringing many technologies relevant to space to commercial viability. The technologies that the commercial world will develop are:

- Technologies for manufacturing many identical spacecraft
- Technologies for efficient spacecraft operations
- Low-cost high-performance electronics and computers
- Technologies for commercial global communications
- Small expendable space launch systems
- Systems-level simulation-based design
- Technologies for automated spacecraft checkout

These technologies will result in standardized, modular bus designs that can be launched on any compatible launch vehicle, simplified payload designs, commoditized payload elements, and efficient (e.g.,autonomous) operations. In addition, the commercial world will develop management techniques to reduce system cost and delivery time as well as refining techniques for cost estimating and scheduling. Relying on the commercial world to develop these technologies, the Air Force will need to invest only where it is necessary to adapt these technologies to meet specific military requirements.

However, not all of the functions needed by the Air Force will be achievable solely with commercial developments.

1.7 Implications of the Vision for the Air Force in Space

The vision for the Air Force in space requires increased capability over projected commercial systems, yet these increases will need to come in a time of decreasing budgets. Therefore, the cost of space systems must be reduced to make these capabilities achievable. The costs of space systems are dominated by the costs of the individual elements, the costs to launch the space elements, and costs to operate them. Historically, the cost of space hardware has scaled directly with mass. To break the current cost paradigm in each of these areas it is necessary to invest in or to invest to adapt from the commercial world several key technologies. The relevant technologies are those that reduce the satellite mass for the same or increased functionality, technologies for launch vehicle cost reductions and performance improvement, and technologies for spacecraft automation.

With the attribute of affordable systems as an overarching consideration, space technology investments can be grouped under the four themes of Global Awareness, Knowledge on Demand, Space Control, and Force Application. These themes will be enabled by targeted investments by the DoD as well as related investments in the commercial sector.

1.7.1 Global Awareness

Global Awareness is the idea that space technology will enable the ability to see in real time everywhere on the surface of the Earth or in the air or near space, under all weather conditions, at any time. The integration of this ability with the command and control system for a military operation will enable the US military to respond and outthink any potential adversary in a context where space-based information will be available on a worldwide basis. The timely acquisition and use of information will confer a tremendous advantage on US forces. Global Awareness also has enormous deterrent value. Any adversaries will know that they are under continuous surveillance by active and passive means at all times, under all conditions.

Global Awareness will be powerfully enabled by Air Force investment in technologies that will make possible large sparse apertures, evolving in the direction of clusters of cooperating satellites. Such systems will enable aperture sizes that are bigger than those now only available with large satellites. In addition, the large number of smaller satellites involved will allow economy of scale in production and will have reduced vulnerability relative to single satellites. Also important to Global Awareness are the technologies for space-based active probing such as synthetic aperture radar, as well as technologies for passive probing through hyper- and ultraspectral sensors. These capabilities will enable any point on the surface of the Earth or the air to be scanned over a wide range of electromagnetic bands.

1.7.2 Knowledge on Demand

Knowledge on demand is the idea that an individual warfighter could request knowledge about some area that he or she is about to enter. The warfighter has always benefited from having strong situational awareness in which he or she is called upon to fight. The human mind is very capable of assessing patterns in information and using those patterns to make decisions. As the infosphere envisioned by the commercial world develops, there will be a plethora of information available at many levels to warfighters. Indeed, there will be so much information to collect, analyze, assess, synthesize, and disseminate that the quantity will be overwhelming. What the warfighter needs is not information, but knowledge. Knowledge will come from a fusion of information from all types of sensor sources (air, ground, and sea as well as space) together with communications to deliver knowledge to the user.

The warfighter could request to see all the new threats in an area or an update on old threats or new targets. That request would be entered into a global integrated information system and if appropriate, a space-based set of sensors would provide the knowledge. The communication would be direct to the system, the request would be processed by the system, the data would be collected by the system, the knowledge would be extracted from the information gathered by the system, and that knowledge would be sent to the warfighter. This use of space-, air-, sea, and ground-based assets combined with Global Awareness will enable direct and timely readout to tactical users. This integrated use of space-based assets is one of the aspects of information dominance and information warfare. The technologies that will enable Knowledge on Demand are the technologies of image processing, secure high-data-rate anti-jam communications, data fusion, artificial intelligence, neural networks, and distributed processing.

1.7.3 Space Control

Desert Storm demonstrated to the world the value of space for warfighting, and historically, the US has operated in space without hindrance. Consequently, US military space forces have evolved into high-value, highly visible, vulnerable targets. As one senior officer said, "We are now in a target-rich environment." The US is not prepared to protect these assets from a Pearl Harbor-type attack. Such an attack could significantly affect the effectiveness of US forces as they become increasingly dependent of space assets.

Control of the battlespace is a key enabling priority for the warfighter. As warfighting has moved from ground to sea to air and now to space, control of each new medium has brought new challenges.

Control of the space medium is similar to the others in that it requires freedom of action in accomplishing objectives (whether they be military, civil, or commercial) while denying similar freedom of action to potential adversaries. While the objectives among the media are similar, the means to accomplish Space Control differ due to the peculiar characteristics of space.

The Space Control mission has three aspects:

- Surveillance
- Protection
- Counter-force operations

The mission of space surveillance is to determine the space order of battle and the background environment. The protection aspect includes all actions required to assure the availability of US space forces, including identifying threats, commanding responses, and designing in capabilities for survivability. The counterforce mission is to disrupt, degrade, deny, or destroy (as appropriate) the space, ground, or command and control segments of the space systems available to an adversary.

Current capabilities to support Space Control are fragmented and do not permit the exercise and training with joint warfighters needed to develop doctrine and tactics. Consequently, the ability to assess the military impact of any offensive counterspace actions is extremely limited. Similar uncertainties exist for defensive counterspace activities. For example, while it may be clear when a radio-frequency interference (RFI) event is a problem for a satellite, characterizing the nature of the interference as hostile is usually impossible with today's technology. Without having confirmation that hostile intent is involved, the RFI instance is usually ascribed to benign sources. It is important that this environment of ambiguity be removed.

The first step in control of the space environment is to develop a comprehensive understanding of what exists in that environment. With the proliferation of nations fielding (or purchasing through commercial arrangements) ever more capable space systems that can be used for military purposes, more extensive effort will be required to characterize the space capabilities of potential adversaries. This must include characterization, not only of systems owned and operated by potential adversaries, but those available through commercial means. Regular surveillance of space to maintain orbital element sets for satellites of interest and to characterize these systems (mission payload assessment or MPA) will be required. Detailed intelligence support will also be necessary to identify the ground segments and other supporting elements of space systems.

As space systems mature, additional challenges to surveillance are arising in keeping track of maneuvering payloads, characterizing smaller size payloads, and coping with the increasing number of payloads in geosynchronous orbit. Current dependence today on a ground-based space surveillance network, with geographic limitations and concerns about annual operating costs, creates severe limitations on the US ability to closely monitor maneuvering payloads. The increasing catalog of active payloads also poses challenges in MPA. Ground sensors are hampered by constraints imposed by viewing geometry, weather, and time of day, requiring a proliferation of sites which is becoming cost-prohibitive. A cost-effective solution to timely maneuver detection, battle damage assessment (BDA), and (perhaps) MPA would be to accomplish this surveillance from space, where a smaller number of sensors could collect more information.

Technologies driven by a space-based solution include: scheduling and tasking algorithms to integrate space assets; autonomous search, detect and track algorithms for space-based sensors, and key technologies to operate these sensors in space environments such as long-life cryogenic coolers and contamination control. Other enhancements include onboard processing and data fusion, as well as low-mass, lightweight and large-aperture optics.

Other, perhaps interim, solutions to stretch the capabilities of existing sites could also aid in the responsiveness of space surveillance. Active laser illumination of satellites of interest supports 24-hour and deep-space collection. Current efforts on the active imaging testbed support this technology. This testbed environment, at Starfire Optical Range, is tackling the technical issues associated with the illumination of a satellite by a laser (beam control, propagation, etc.) which will allow tracking and imaging during hours of darkness.

Detailed satellite of interest characterization is required for development of the space order of battle. Collection of multi-phenomenology data will aid in the MPA process with the resulting information then fused and stored in interactive databases to support threat analysis and targeting. Efforts in hyperspectral imaging, optical interferometry, and signature data exploitation techniques support these needs.

To protect space systems, the segments must be hard to find, hard to track, hard to discriminate, and hard to damage or kill. The key first steps in protecting space systems come from continual monitoring of potential threats and early warning when a friendly satellite is receiving increased interest by potential adversaries. At a minimum, it will be necessary to detect when friendly satellites receive increase scrutiny by active tracking. Recent successful operations of the Technology for Autonomous Operational Survivability (TAOS) satellite have aided in this understanding. Small, lightweight, low-power packages capable of detecting and geolocating a wide variety of threats are within current technology. Further miniaturization will facilitate integrating these receivers on a broader array of space assets.

Key protection technologies include: low observability, maneuverability, shielding, self-sensing and self-healing systems, and proliferated or distributed architectures.

The protection of the ground and command and control segment of space systems is also vital. Security countermeasures such as intrusion detection, access control, and proliferation are typically used. As the consolidation of ground elements is being pursued, a careful nodal analysis that examines the vulnerabilities of US systems must be performed to ensure that adequate protection is maintained. Increased spacecraft autonomy will minimize the need for contact with the ground and thereby reduce vulnerability.

Counterspace negation options must evaluate all segments of the space system and its supporting infrastructure. Existing capabilities are predominantly focused on ground and command and control segments. In the space segment, classic efforts in satellite negation have focused on kinetic-kill and directed energy applications for disruption, denial, degradation, and destruction. Technologies in these areas are at a sufficient maturity level to initiate a program. Other emerging technologies, specifically, high power microwave capabilities and techniques tied to information warfare, could be brought to bear in this area.

As civil and commercial space capabilities in the areas of navigation, communications, weather, and remote sensing increase in number and capability, more attention must be paid to preserving US advantage while adversaries use these systems for military purposes. Denial of GPS data is a classic example of this.

Future US Space Control capabilities must allow for true control of the space environment with the same surety as other mediums. The picture of the space environment must be complete to include a detailed understanding of all on-orbit systems an adversary could exploit (military, civil, and commercial) and all capabilities used to support friendly military forces. This detailed picture supports the development of options for Space Control protection, prevention, and negation. Space Control capabilities must be available to allow engagement of all space capabilities available to potential adversaries. Key US space systems must be hardened to withstand or avoid attacks. Space systems and data must be controlled to prevent adversary access to either the space-derived information or the space asset itself. This prevention must be accomplished while still allowing US/Allied warfighters access to the data. Adversary access to space must be negated by identification of the key vulnerable nodes and denial or elimination of the node. Key to the success of these options will be a timely assessment of their effectiveness supporting re-targeting for ultimate control of space.

1.7.4 Force Application

The current Air Force mission area of Force Application includes both nuclear and conventional deterrents to place adversary terrestrial targets at risk. The technology for precision kinetic energy strike of fixed terrestrial targets from space-based or ballistic missile platforms is available to the US now. Technologies such as microelectromechanical systems (MEMS) could substantially improve the affordability of such systems. Technologies for similar conventional strike of mobile targets are possible given the appropriate targeting and command and control. Discussion of this kind of capability has so far focused on a very limited capacity for a narrow range of targets. However, the technology suggests the possibility of a dramatic change in the means available for global power projection, making logistic delay negligible and recovering the investment in energy for logistic deployment directly as destructive energy on targets. The equivalent of the Desert Storm strategic air campaign against Iraqi infrastructure would be possible to complete in minutes to hours essentially on immediate notice.

US perspectives on this kind of capability are colored by past investment in conventional force projection and by cold war attitudes about deterrence. The use of ballistic missile platforms for conventional strike raises an ambiguity in nuclear deterrence that would have been destabilizing in the bipolar cold war context. Use of orbital platforms for conventional strike raises a similar ambiguity regarding verification of the treaty banning weapons of mass destruction in space. The opportunity for others to exploit this avenue to global power will be readily accessible to the large community of nations achieving access to space. Awareness of this opportunity should help motivate Air Force investments in Force Application and missile defense.

1.8 Report Organization

The remainder of this report covers specific space technology areas. Chapter 2 discusses space launch technologies, including both expendable and reusable launch vehicles. Chapter 3 reviews spacecraft bus technologies such as power, propulsion, structures, and other subsystems that are common to all space assets. Chapter 4 discusses spacecraft payload technologies, including sensors, communication systems, and onboard processing. Chapter 5 discusses spacecraft manufacturing, operations, and software as issues that cut across the launch, bus, and payload areas. Finally, Chapter 6 contains a summary of the Space Technology Panel's conclusions and recommendations.

Within each technology area, the report identifies specific technologies for revolutionary change in which the Air Force must invest, technologies for evolutionary change in which the Air Force should invest, and technologies that will be led by the commercial sector in which the Air Force should invest to adapt.

Appendices A through C describe the charter of the Space Technology Panel, provide information on the panel members, and list the meetings the panel held. Appendix D is a compilation of the acronyms used in this report. Appendix E summarizes other relevant reports on space technology, while Appendices F and G list the white papers and briefings that the panel received during the New World Vistas study.